iv. Standard Aperture Quadrupoles

The two rings require 276 arc quadrupoles and 144 insertion quadrupoles of standard 8 cm aperture. The magnetic length of the arc quadrupoles is 1.11 m and of the insertion quadrupoles Q4 1.81 m; Q5, Q6, Q8, Q9 1.11 m; Q7 0.93 m.

There are strong economic and technical reasons for maximizing commonality of the designs for all the magnet types; thus the quadrupole is based as much as possible upon the dipole design discussed above. Parameters which have been chosen to be identical are: 1) superconducting cable; 2) operating current; 3) cryogenic design; 4) beam tube; 5) one-layer coil; 6) coil radii; and 7) yoke assembly.

The arc quadrupoles, sextupoles, correctors, and beam position monitors need to be accurately located with respect to the beam and relative to each other. For this reason, they are designed to form one rigid mechanical assembly, as shown in Fig. 4-1 . All insertion quadrupoles have a corrector package, and half of the Q9 insertion quads also have a sextupole magnet.
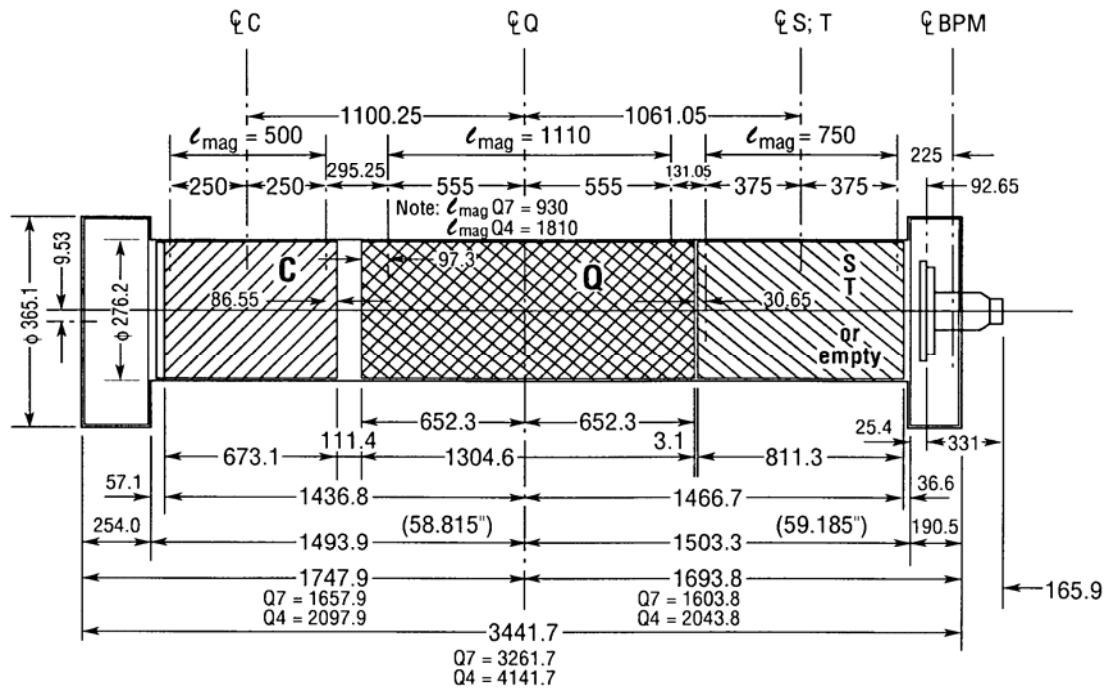

Fig. 4-1. Corrector, quadrupole, sextupole (CQS) assembly. Lamination length is shown (dimensions in mm).

The quadrupole coil design is based on a single-layer "cosine two-theta" coil, wound from a partially keystoned, 30-strand NbTi superconducting cable and mechanically supported by a laminated "cold steel" yoke encased in a cylindrical stainless steel helium containment vessel which is common to the corrector and sextupole. The helium vessel is also a load-bearing part of the yoke assembly. This cold mass assembly is mounted within a cryostat consisting of a cylindrical vacuum vessel, an aluminum heat shield, blankets of multilayer thermal insulation, cryogenic headers, and the magnet support system. Figure 4-2 shows a cross-section of the quadrupole magnet proper or "cold mass." The principal arc quadrupole parameters are given in Table 4-1. The nominal arc gradient requirement is ~71 T/m at top energy, which is obtained with a current of 4.72 kA. The insertion quadrupoles require up to ~6% higher gradients. Larger tuning capabilities are provided by trim quadrupoles at Q4, Q5, Q6.

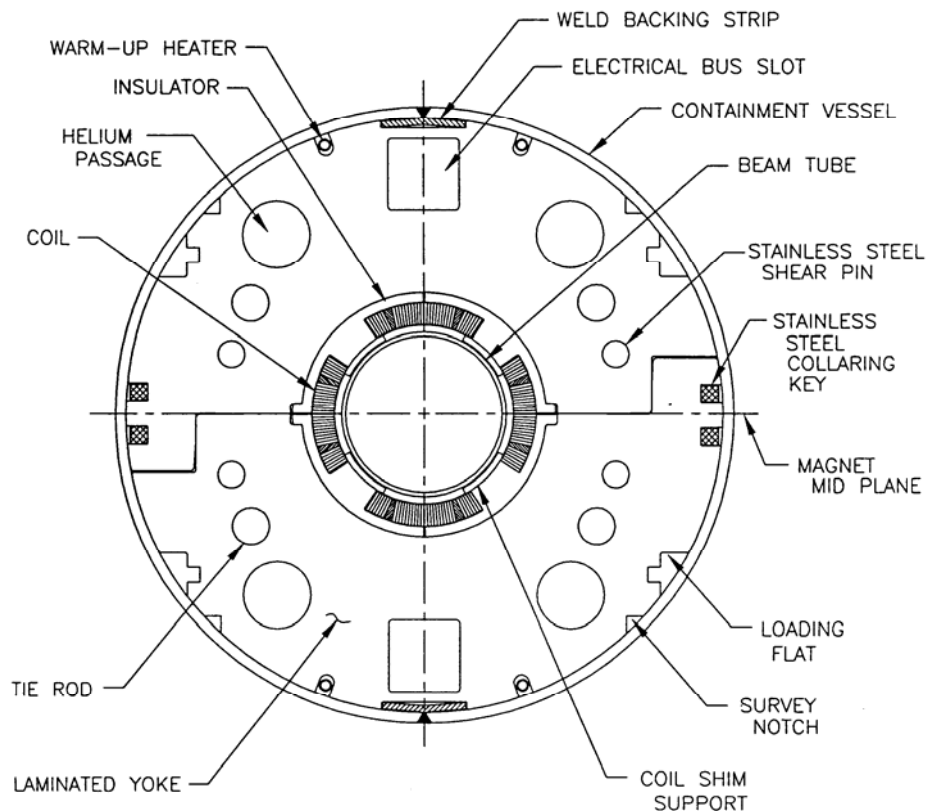**Fig. 4-2.** RHIC Arc Quadrupole cross-section (coil i.d. = 79.9 mm).

Table 4-1. Standard Aperture Quadrupole Design Parameters

Coil i.d.	(3.146 in.) 79.9 mm
Coil o.d.	(3.938 in.) 100.0 mm
Number of turns per pole	16
Number of turns, 1st block (closest to pole)	6
Number of turns, 2nd block	10
Wedge angle, bare	13.6 deg
Wedge height, bare	(0.396 in.) 10.06 mm
Effective cable mid-thickness with insulation under compression	(0.05292 in.) 1.344 mm

ARC QUADRUPOLES

No. quadrupoles, arc	276
Gradient, @ top energy	~71 T/m
Current, @ top energy	4.72 kA
Gradient, quench	107 T/m
Current, quench	7.65 kA
Magnetic length, arc	1.11 m
Lamination length	(48.4 in.) 1.23 m
Coil length, overall	(48.75 in.) 1.24 m
Coil length, straight section	(39.78 in.) 1.010 m
Cable length per magnet	(504 ft) 154 m
Cable mass per magnet	(27.8 lb) 12.6 kg
Cold mass, CQS package	(2091 lb) 948 kg
Inductance	~2 mH
Stored energy at top energy	20 kJ

INSERTION QUADRUPOLES

No. quadrupoles,	1.81 m - Q4	24
	0.93 m - Q7	24
	1.11 m - Q5, Q6, Q8, Q9	96
Gradient @ top energy, Q4, Q5, Q6		75.5 T/m

The quadrupole utilizes a cold stainless steel beam tube of ~69 mm inner diameter. The beam tube design for the CQS package follows the dipoles, except that bumpers are not used because the CQS assembly is straight. The superconducting coil is assembled from quarter-coils that are wound on automated machinery and then formed into a specified size in a precision molding operation - much like the dipole coils. It consists of a single layer of 16 turns per quarter-coil arranged in two blocks with an intervening copper wedge; the size and positions of the wedge and the coil pole spacer have been designed to result in a single-layer coil with field harmonics meeting the rigid field quality specifications required for RHIC. The conductor is the same as that used in the arc dipoles. The cable is insulated with two 50% overlap layers of Kapton film coated with a polyimide adhesive.

The quadrupole yoke design follows directly the dipole design. The yoke laminations are punched from 6.35 mm thick low-carbon steel plate. The lamination surface is phosphate treated. During magnet assembly, a press is utilized to load the coil-in-yoke assembly; it is subsequently held together with stainless steel keys on the outer steel surface to the design preload at room temperature of nominally 69 MPa acting on the coils. After completion, the quadrupole cold mass assembly, together with the sextupole and corrector cold mass assemblies, is inserted snugly into the two halves of a 4.9 mm thick, split stainless steel shell which is then welded along the vertical midplane. The welding operation forms the outer, high-pressure (2.1 MPa) helium containment vessel. This vessel also gives the structure its rigidity and maintains the relative alignment of the component cold masses, which is established by fixturing during the welding operations. This overall assembly is referred to as the CQS cold mass assembly. The CQS assembly is mechanically similar to the dipole assembly, performed with much the same tooling; the principal difference is that the CQS assembly is straight, with no sagitta. The shrinkage of the welds on solidification causes compression of the steel collar blocks, relieving the stress on the keys. Additional compression of the blocks is caused by differential contraction of the stainless steel shell relative to the steel yoke. Since the yoke is completely closed during keying, the coils do not experience any of this increased compressive force.

The design requirements for quadrupole beam tube, yoke, and yoke containment shell are given in Table 4-2.

Table 4-2. Quadrupole Beam Tube, Yoke, and Yoke Containment Shell Parameters

---

CQS BEAM TUBE

Outer diameter, bare	(2.875 in.) 73.0 mm
Wall thickness (0.077 in.)	1.96 mm
Weight, nominal	(29 lb) 13.4 kg
Beam tube-coil radial gap	(0.133 in.) 3.4 mm
Magnetic permeability, 300 K	< 1.005

ARC QUADRUPOLE YOKE

Inner diameter	(4.300 in.) 109.2 mm
Outer diameter	(10.500 in.) 266.7 mm
Lamination length	(48.4 in.) 1.23 m
Length, including end plates	(51.36 in.) 1.305 m
Lamination thickness	(0.250 in.) 6.35 mm
Length, lamination packs	(0.500 in.) 12.7 mm
Weight of steel	(773 lb) 351 kg
Bus cavity width, height	(1.25 in.) 31.75 mm
Number of cooling channels	4
Diameter of cooling channels	(1.187 in.) 30.15 mm

YOKE CONTAINMENT SHELL

Inner diameter (prior to assembly)	(10.516 in.) 267.1 mm
Wall thickness	(0.192 in.) 4.9 mm
Weight of common shell for CQS	(215 lb) 97.5 kg
Assembly prestress - Room temperature	(10 kpsi) 69 MPa
- Cold	> (4.8 kpsi) 33 MPa

All quadrupoles quenched well above their operating current and most reached the conductor limit in a few quenches (Fig. 4-3). Measurements of the integral quadrupole field and the first allowed term are shown for a typical quadrupole in Figs. 4-4 and 4-5 . Measurements of the transfer function during injection and the initial part of the ramp up are shown in Fig. 4-6 for a Q7

quadrupole. Measurement conditions were essentially identical to those for the dipole measurements discussed previously, except that the measuring coil was 0.23 m long. The drift and snapback of the dodecapole were ~ 1.5 units.   Field quality data for the quadrupoles are summarized in Table 4-3.
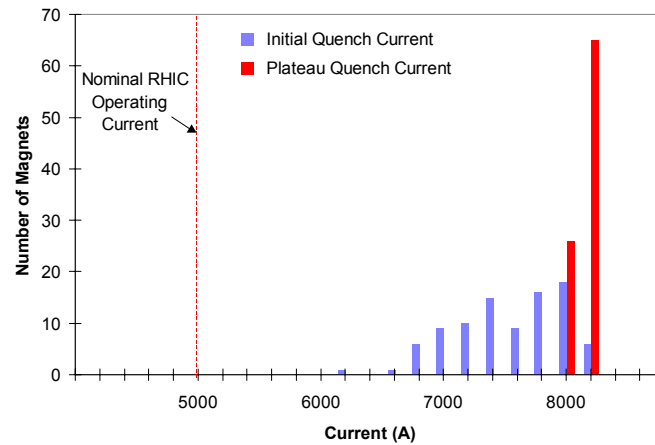

Fig. 4-3. Quench performance of 91 arc quadrupoles, tested at 4.5 K. The average plateau quench current of these 91 magnets was 8152 A.
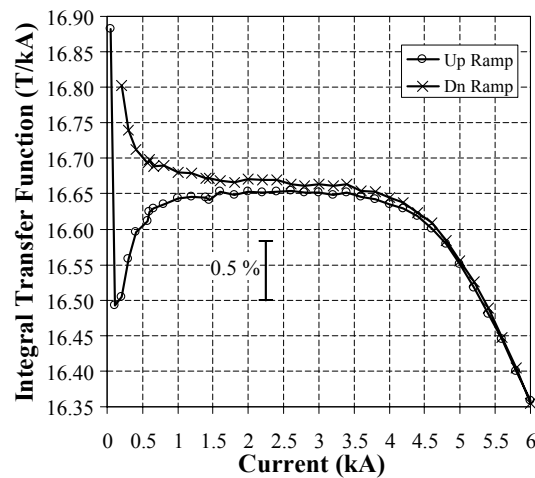

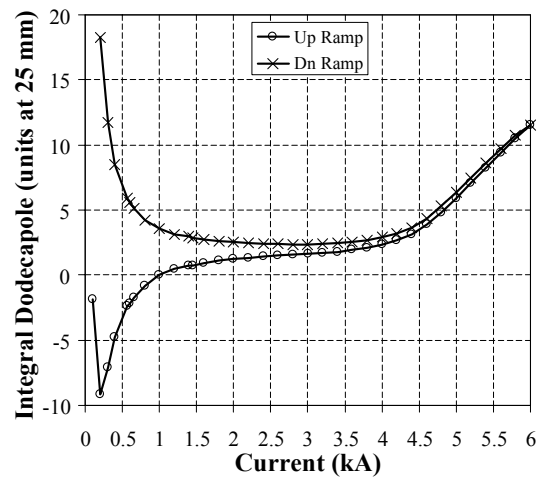**Fig. 4-4.** Integral transfer function in QRG316.
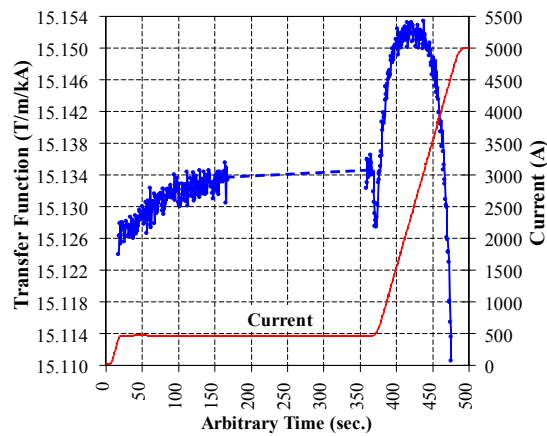
Fig. 4-5. Integral dodecapole in QRG316.

Fig. 4-6. Time decay and snapback in QR7109.

Table 4-3. Summary of Integral Field Quality in RHIC Arc Quadrupoles.

Harmonic at 25 mm	Mean		Standard Deviation	
	10 A (380 magnets)	5000 A (91 magnets)	10 A (380 magnets)	5000 A (91 magnets)
b_2	-0.61	-0.21	1.61	1.77
b_3	-1.51	-0.61	0.95	1.39
b_4	0.14	0.57	0.49	1.57
b_5	1.42	5.70	0.42	0.62
b_6	0.01	0.05	0.13	0.13
b_7	-0.52	-0.52	0.09	0.11
b_8	0.01	0.06	0.05	0.14
b_9	-1.29	-1.44	0.06	0.08
b_{10}	0.00	0.00	0.02	0.02
a_2	-1.93	-1.83	1.66	1.68
a_3	0.48	0.23	0.95	0.90
a_4	0.06	-0.26	0.48	1.40
a_5	-3.76	-3.84	0.29	0.31
a_6	0.04	0.06	0.13	0.14
a_7	0.01	0.04	0.11	0.09
a_8	0.00	0.03	0.05	0.10
a_9	0.35	0.39	0.02	0.04
a_{10}	0.00	0.00	0.02	0.02